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State of the art monitoring solutions of water retaining structures

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Abstract

The monitoring of local and distributed temperature and strain measurements in embankments of reservoirs and canals, with respect to leakage detection and displacements, has increased in recent years.

Over the last two decades, different monitoring techniques have been developed and successfully implemented in various types of water retaining structures, such as dams and embankments, to recognise degradations of structures in time. The data collection and interpretation are fully automated. The measurements can be analysed in real time using a web-interface. Indicative thresholds are identified after a test period to establish a site-specific alarm system. The monitoring system enables early detection of potential structural integrity issues so that immediate mitigation measures can be taken to reduce the risk of structural failure.

This paper outlines these methods – including the Gradient-Method and the Heat-Pulse-Method for leakage detection as well as the permanent measurement of relative strain changes for movement detection – through more recent installation examples in the United Kingdom.

Keywords: Temperature, Strain, Leakage monitoring, Movement monitoring, Dam

1. Introduction

The early detection of any seepage, movement or deformation of water-retaining structures is critical to ensure the long-term integrity and safety of dams and embankments. Regular or continuous monitoring is necessary to predict and prevent catastrophic failures. It provides time for risk reduction activities and prompt implementation of essential repairs if needed.

The thermal investigation methods were originally based on pointed temperature measurements in the body of embankments and dams to locate seepage zones (Kappelmeyer, 1957). These measurements were sometimes recorded over time to estimate other hydraulic parameters such as the effective flow velocities (e.g. Dornstädter and Heinemann, 2010). During past years, the Distributed Temperature Sensing (DTS) and Distributed Temperature and Strain Sensing (DTSS) methods have been developed and increasingly used to assess strain and temperature changes for multiple industrial needs, including embankment monitoring (e.g. Aufleger et al., 2011; Dornstädter and Dutton, 2016; Fabritius et al., 2021, 2017).

Depending on the purpose of the auscultation, the size of the sites, the possibility of intervening during construction or on an existing structure (retrofit), each method of investigation has its fields of application today. To meet the needs of a project, choices must be made among the following:

- **Installation of sensors:** Will the sensors be installed from the surface, on an existing structure (probes, trenches, retrofit), or in the body of the structure during construction or major rehabilitation work (raising, sealing wall, lining, etc.)
- **Type of sensors:** Will chains of point sensors (i.e. PT100/PT1000 or digital sensors) be installed, or distributed temperature and/or strain optical fibres (DTS / DTSS), generally retained for large-scale sites.
- **Appropriate method:** The leakage detection applying the Gradient-Method is reserved for cases when there exists a temperature difference between the water in a reservoir/canal and the ground at the sensor location; the Heat-Pulse-Method applies to the leakage detection when this last condition is not met. The Strain-Sensing-Method is necessary when displacements are to be monitored (sliding).
- **Duration of survey:** Depending on the investigation objective, a momentary measurement (leak detection), repeated or continuous measurements over a defined period (flow velocity estimation, change in condition) or permanent measurements for long-term monitoring (surveillance, control) of the structure are possible.

The selection of sensor types and their installation options, as well as the choice of the method and the measurement duration, allow a response tailored to the needs of a project.

2. In-situ temperature and strain investigation: general considerations

Ground temperatures and strain measurements in water-retaining structures are indicative for seepage through and displacements within the structure. The different interpretation methods of these data are listed hereafter.

2.1 Temperatures

The temperatures of the air, the surface water and the ground vary according to the seasons. At shallow depths (i.e. up to 1-2m), temperature variations in the soil are almost synchronous with the temperature of surface water and air. At greater depth, temperature variations in the soil show a phase shift relative to the temperature of the reservoir or canal water, due to the low thermal conductivity of soils and other building materials. Furthermore, according to the heat capacity of the soil, the amplitude of seasonal temperature variations of the ground decreases with depth.

The leakage detection by the Gradient-Method is based on changes of absolute ground temperatures caused by seepage water (Kappelmeyer, 1957). This method is limited to cases with a temperature difference between the seepage water and the dam material. In regions with temperate climate, fluid flow in the subsurface leads to temperature anomalies because the fluid has a temperature different from the ground, through which it migrates, at nearly any time of the year. Thus, the temperature of the seepage water is used as a tracer to detect and locate zones with increased seepage. In winter, the temperature of the water is significantly colder than that of the ground, while in summer the opposite is the case.

Continuous ground temperature and water temperature measurements reveal anomalous phase shifts where ground temperatures are disturbed by seepage water. The time lag between an obvious variation seen in the water temperatures, and this same variation observed in the ground is the time needed for seeping water to flow from the entry point to the measurement point. By determining phase shifts and indicating a flow path length, pore velocities are estimated at the location of the sensor. Pore velocities of the order between 10^{-3} m/s (daily variations showing time shifts < 1 day) – indicating risks of internal erosion – and 10^{-6} m/s (seasonal variations showing time shifts of 2-3 months) can been determined with satisfying accuracy.

In some cases, there is no significant temperature difference between the water in a reservoir/canal and the ground. This situation occurs in equatorial regions and, of interest to European sites, when the temperature sensors are placed very close to the reservoir water, e.g. behind joint seals, behind asphalt or concrete linings or at shallow depths. To overcome this limitation, a second approach is preferred – the Heat-Pulse-Method. When the near field around the temperature sensors is heated, zones of higher water saturation or seepage flow are distinguished by an increased heat dissipation, i.e. they heat up less compared to zones with lower water saturation. Furthermore, the HPM can be used to estimate the effective thermal conductivity of the ground material. Anomalous effective thermal conductivities are valuable thresholds for ranking the leakage detection. They are calculated by analysing the heating and cooling curves during a Heat-Pulse test (e.g. Dornstädter et al., 2008). The HPM is compatible with both temperature sensor chains and DTS measurements. In the former case, the thermal probe can be heated by means of heating rods or cooled down with liquid CO_2. DTS measurements use a hybrid cable consisting of optical fibres for temperature measurements and copper wires to heat the ground with a known electrical power (e.g. Aufleger et al., 2008, 1998; Dornstädter, 1997).

2.2 Strains

The latest developments in data acquisition via fibre optic cables consist of continuous strain detection which reveals displacements/movements along the installed cable. A particular innovation presents the combination of Distributed Temperature and Strain Sensing (DTSS). In difference to temperature measurements by means of optical fibres, which use the temperature-dependent backscattered Raman spectrum, the DTSS method makes use of the phenomenon of Brillouin scattering, which leads to a light frequency shift that depends on both the local mechanical (strain) and thermal (temperature) state of an optical fibre. For the strain measurement, the optical fibre is rigidly glued in place. Strain events as small as 100 µStrain (10cm/km) disturb the backscattered Brillouin-spectrum and are thus detected and localised.

3. In-situ temperature investigation - example in the United Kingdom

Considering that more than 500 km of dyke segments, about twenty lock chambers, ten weirs and 80 dams have been investigated during the past 30 years, all described methods were experienced. Leaks in sealing elements and zones of increased permeability in the dam body or its foundation could be detected and exactly localised. The different investigation methods were applied to hydraulic structures in the United Kingdom as shown hereafter. Their advantages and limitations are outlined.

3.1 Single temperature survey on a canal section

An instantaneous temperature survey on a 160 m long section of channel in England was recently performed (2022). The investigation took place on an existing embankment using temperature probes. Hollow metallic tubes, made up of successively threaded rods, were driven into the ground up to 10 m depth. Temperature measurements within the tubes were carried out by means of chains of temperature sensors (PT100), spaced 1 m apart. Temperature measurements in a set of tubes, spaced at 10 m centre, provided a 2D visualisation of the ground temperatures along the array of probes. A first data analysis was immediately carried out on site, so that the survey mesh could be refined to find the largest temperature anomaly.

The temperature anomalies, identified from ground temperature measurements, can be compared to the surface water temperatures to provide an indication of the seriousness of the seepage. Ground temperatures close to water temperature (Fig. 1) indicate important seepage flow with the attendant risk of internal erosion and instability.

The instantaneous temperature survey allowed mapping temperature anomalies (leakage detection) and provided a reliable delimitation of the vertical and horizontal boundaries of the seepage zone (Fig. 1). As a result, sealing work is planned on this section of the canal, followed by a control investigation by a temperature survey.

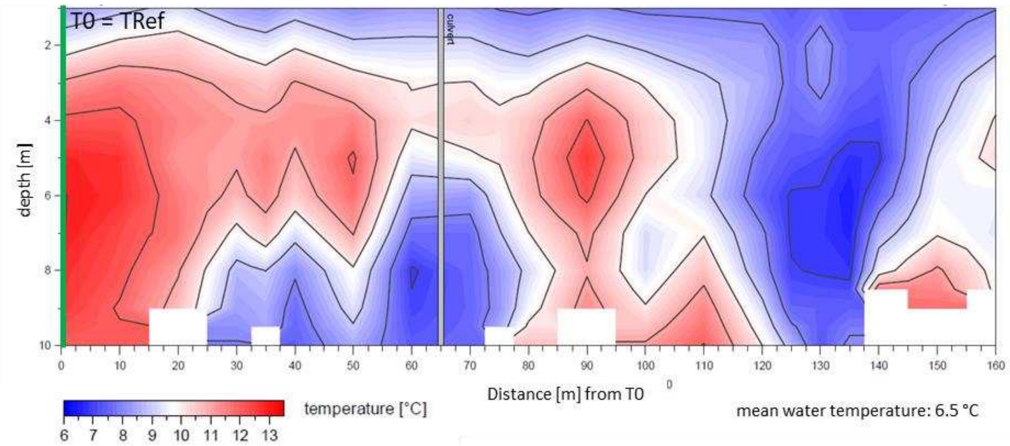

Figure 1:2D-illustration of ground temperatures on a vertical section of the array of probes in England.

3.2 Repeated temperature surveys

The second example concerns repeated temperature measurements in permanently installed thermal probes. First studies started in 2006. Temperature surveys were repeated every 6 months which provide the surveillance of the evolution of observed leakage zones. The repeated surveys facilitate the decision on whether to carry out sealing work on specific sections. As an example, cold temperature measurements recorded between 2 m and 6 m of depth during winter 2015 indicate a seepage zone on one of the canal sections (Fig. 2A). Renewed measurements in winter after remedial works prove a return to normality of the temperature distribution (Fig. 2B).

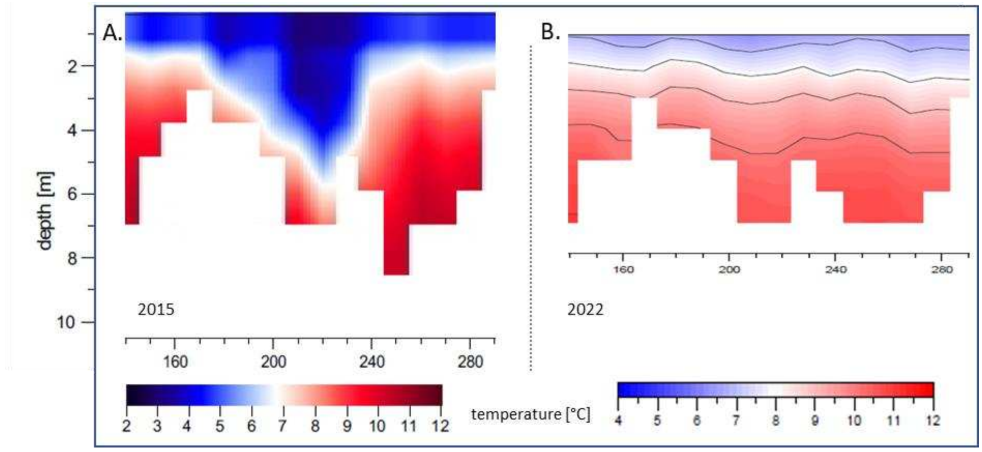

Figure 2: Thermal investigation of a canal section in Wales, before (left) and after (right) remedial work.

3.3 Continuous temperature monitoring for the estimation of pore velocities

Following the discovery of two sinkholes in the towpath of a canal section, four thermal probes were equipped with a data logger to perform continuous ground temperature measurements at several depths, during a period with changing water temperature. In the aforementioned example, the temperature survey indicated significant seepage around the locations of the two observed depressions. The ground temperature was close to water temperature. The length of the flow path was estimated to 5 m, and the measured time shifts at 2 m and 3 m depth were about 1 day and 2-5 days respectively (Fig. 3). The most significant anomalies at 2 m depth revealed flow velocities (pore velocities) of the order 10^{-5} m/s. Further long-term observations, which could include remote temperature monitoring, provide a trend of phase shifts over time: an increase indicates an improvement in condition, unchanged values indicate an unchanged condition, a decrease indicates a deterioration that might progress to internal erosion.

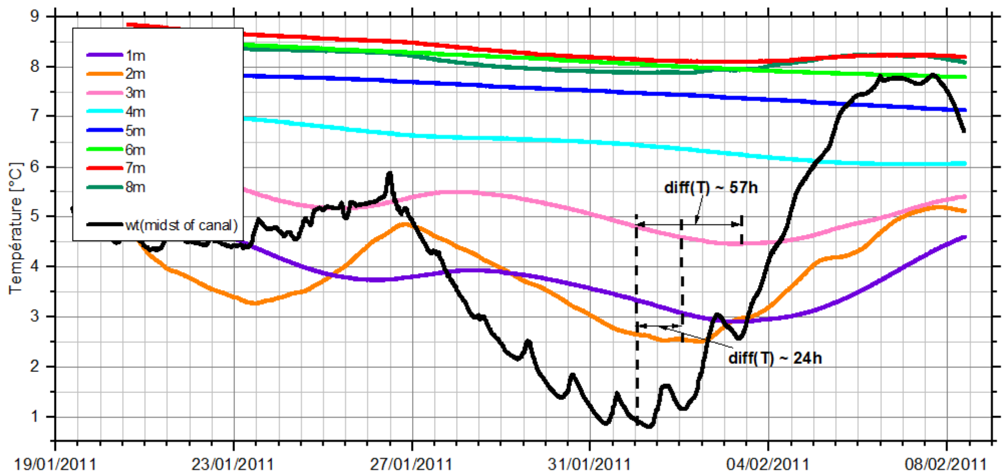

Figure 3: Thermal investigation of a canal section Wales, continuous measurements at a thermal probe at different depths.

3.4 Permanent installation of a DTS system

For projects aimed at monitoring larger structures, the number of temperature data points required for optimal monitoring becomes considerable. In such cases, distributed temperature sensing (DTS) measurement – which enables high resolution temperature measurements along a conventional optical fibre of up to 70 km length – constitutes a smart alternative to sensor chains and loggers.

A DTS-based permanent temperature monitoring system was implemented in an existing earth fill dam in West Yorkshire to survey its condition with respect to seepage occurrence. Since this is a completed dam, the fibre optic cable was placed in the dam by means of temperature probes (retro fit). For this purpose, optical fibres with a bending diameter of 8 mm without significant loss-of-signal were newly developed. The fibres were looped back within the fibre optic cable itself to be inserted into the hollow tubes of the probes.

The thermal probes were rammed into the dam and its foundation to a maximum depth of 29 m (outlined in Fig. 4). The integration of optical fibres in the structure was designed to accurately localize emerging leaks through permanent temperature monitoring. No evidence of seepage has been identified so far at any of the installed soundings.

The fibre optic leakage detection system operates as a standalone system and can be remotely accessed. The leakage detection system has been combined with a visualisation software for fully automated measurement transfer and data evaluation. Current measurements together with historical events are displayed on the web-based visualisation, providing a fast and clear overview of the performance of the structure. In the event of seepage, an alarm is generated based on the automatic evaluation of the data and the corresponding trigger levels/thresholds defined. The alarm is indicated on the screen by the dam section displayed being highlighted in colour according to its condition: green = ok; yellow = observation; red = danger. On demand, alarm signals can be automatically forwarded via E-Mail/SMS.

The leakage detection and seepage monitoring system are based on the recording of absolute temperatures (Gradient-Method), i.e. the deployment of fibre optic cables without the possibility of heating. Since the installation of hybrid cables allows the use of both the Gradient-Method and the Heat-Pulse-Method, the installation of a hybrid cable is recommended in order to obtain detailed and additional information to the Gradient-Method or the Heat-Pulse-Method if required (Dornstädter and Dutton, 2016).

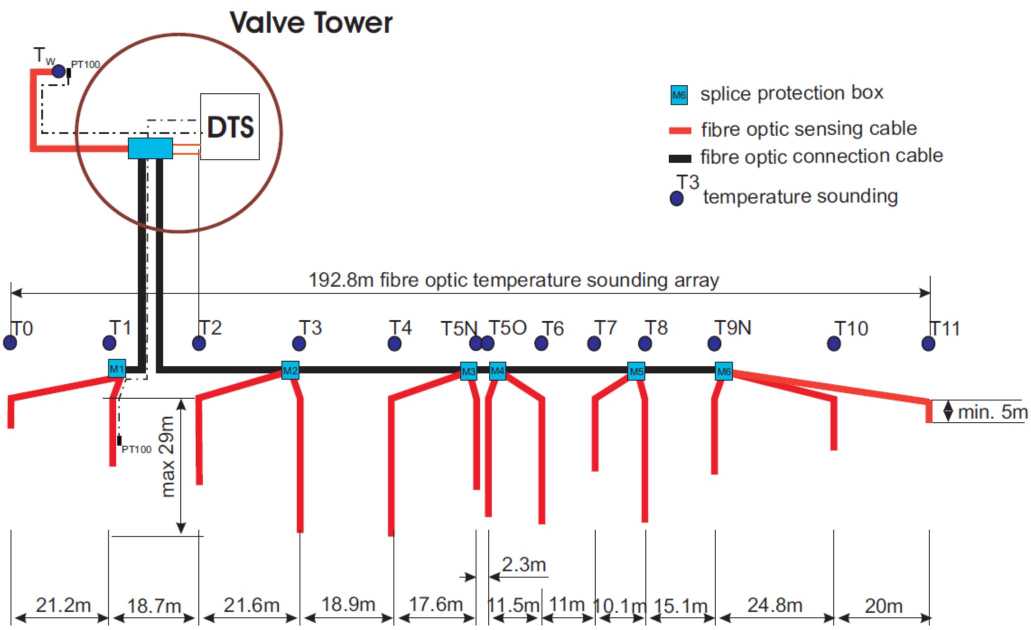

Figure 4: Schematic overview of the fibre optic leakage detection system installed on an existing earth fill dam in West Yorkshire (not to scale).

3.5 Permanent monitoring of an underground service reservoir with DTS measurements: application of the HPM method

New service reservoirs are made of pre-cast concrete walls. They incorporate numerous wall joints, which represent a bacteriological failure risk in the long term, especially if these joints can no longer be inspected (backfilling on the outer walls of the container). To control the risk of failure, a leakage monitoring system was installed in 2018 (under construction) on a 45Ml service reservoir, by installing a fibre optic cable in a meandering pattern along the joints on the reservoir wall (Fig. 5A). The monitoring system uses a distributed fibre optic temperature sensing (DTS) with a spatial resolution of 0.7m. Since the installed sensors are close to the retained water, a hybrid fibre optic cable was used (optical fibres and copper wires), allowing repeated Heat-Pulse tests performed on a weekly basis. As for the previous example, the measurements are automated and, in case of detected flow, an alarm is generated (Fig. 5B). When commissioning the monitoring system, a leakage has been simulated by pouring water at a rate of 0.3 – 0.4 l/s on the top corner of one of the pre-cast concrete elements.

This resulted in a reduced temperature difference during the Heat-Pulse test, demonstrating the functionality and high sensitivity of the system (Fabritius et al., 2021).

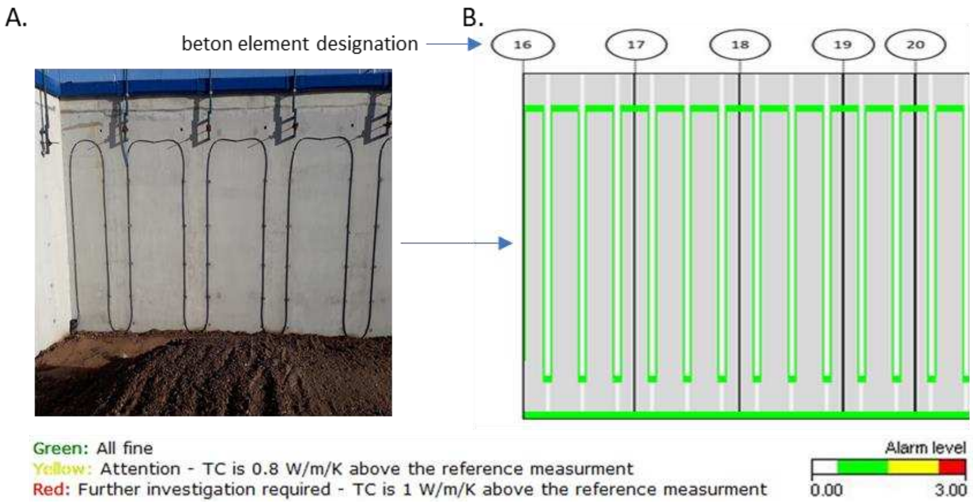

Figure 5: A. Cable fixed on the wall of the service reservoir; B. Visualisation of a Heat-Pulse-based alarm.

3.6 Permanent monitoring of a sludge lagoon with DTS (Heat-Pulse Method) and DTSS measurements

The last example is an innovative combined leakage and movement early detection system put into operation in November 2019, as a key part of the £7Mio investment to monitor the risk of a century old sludge lagoon. The system is based on distributed fibre-optic sensor methods for measuring temperature and strain (DTS and DTSS methods). Two types of fibre optic cables, a hybrid cable for accurate temperature sensing (DTS) including Heat-Pulse-Method and a specific strain cable (DTSS), have been placed in trenches along four different sections of the entire lagoon embankments (about 5 km cable of each type) to monitor temperature and strain change. Three methods, described by Fabritius et al., 2021, are applied for the site monitoring:

- **Fire alarm:** Sludge lagoons are susceptible to internal combustion that can be controlled directly by temperature measurement.
- **Leakage alarm:** The Heat-Pulse-Method was used weekly for leakage detection (Fig. 6 left). To date, no leaks have been detected. The evaluation in terms of effective thermal conductivities shows spatial heterogeneities consistent with the nature of the environment in which the fibre is placed (soil vs. road, embankment crest, slope or toe).
- **Movement alarm:** The permanent monitoring of relative strain changes along the fibre (DTSS) allows the detection of dam movements such as settling or sliding (Fig. 6 right). Strain data acquisition is performed on an hourly basis. Sudden strain variations (within 24 hours), even of lowest amplitude, can indicate the onset of rapid ground movement and would be detected. Strain changes after 1 week are also evaluated, indicating even smaller movements.

The data recordings and their interpretation are fully automatic and can be analysed in real-time via a web interface. During a test phase, trigger thresholds were set and linked to an automatic alarm system that complements on-site surveillance.

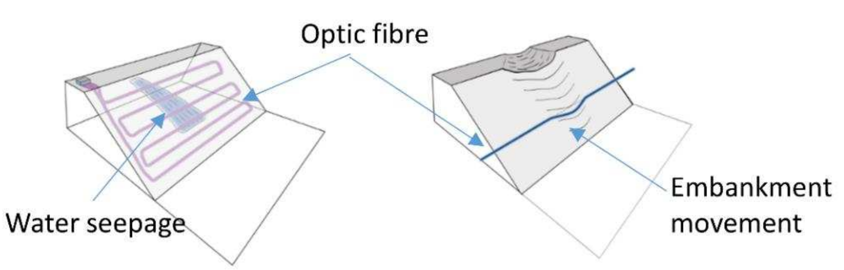

Figure 6: Basic principle of fibre optic sensing for leakage (temperature, left) and movement (strain, right) monitoring in embankments.

4. Outlook and conclusion

Leakage detection methods based on temperature measurements were already applied for various projects demonstrating a high degree of sensitivity and reliability. These investigation methods prove to be very versatile and adapt to the constraints of the site and the needs of the clients.

Many years of experience with this measurement technique have shown that a multitude of technical and environmental questions can be answered with a reasonable technical and financial effort. In-situ temperature measurements (and their variation over time) directly and clearly delimit the seepage zones and assess their seriousness. Repeated measurements make it possible to follow the development of the condition (erosion, pore clogging, etc.) and the continuous monitoring of temperature measurements along an array of temperature probes gives reliable indications of pore velocities.

The Heat-Pulse-Method has the advantage of being applicable whatever the temperature environment around the temperature sensors is.

When the scope of the project justifies it, the use of distributed measurement along optical fibres offers a particularly interesting and cost-effective alternative to measurements by point sensors. Distributed Temperature Measurement (DTS) allows the application of the Gradient-Method and the Heat-Pulse-Method (via hybrid cables) for leakage detection. Distributed temperature and stain sensing (DTSS) allows the detection and localisation of small ground movements. This technology supplements temperature measurements to monitor the integrity of hydraulic structures.

All described methods have proven practical applicability, reliability and cost effectiveness.

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